SnowMass2021

Snowmass EF03:
Heavy flavor and top quark physics

Reports Reading and Discussion

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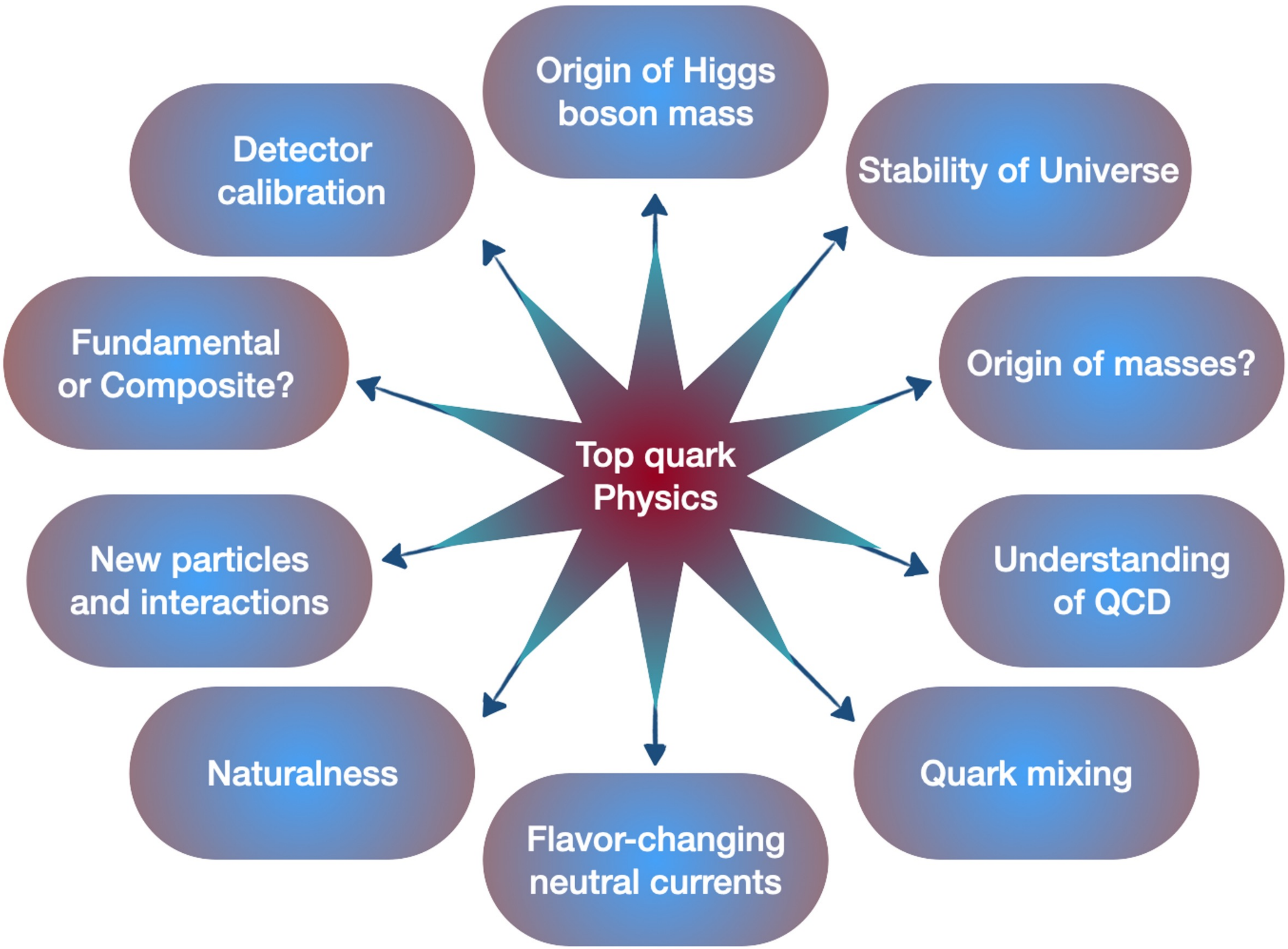
Heavy flavor and top quark physics



Heavy flavor and top quark physics

- Prospects for precision measurements (HL-LHC,FCC-hh,FCC-ee,ILC, CLIC, muC):
  - top quark properties: mass, width, electroweak couplings
  - study of rare processes: ttW, ttZ, tZq, tttt, FCNC, compositeness,…
  - precision measurements of a wide variety of observables and in new kinematic regimes: spin correlations, polarization, boosted top, …
- Joint studies:
  - m_{top} in global electroweak fits (with EF04)
  - Top quark couplings and global EFT fits (with EF04)
  - Top and HF in PDF fits: extraction of gluon PDF, alphas, ... (with EF06)
- Prospects for HF physics (b,c,s) at future colliders
  - Full pattern of quark couplings, running b-quark mass
- Status of predictions and prospects for theory improvements:
  - Interpretation of m_{top}, new ideas for m_{top} measurements
  - Higher order QCD and EW corrections, scale and renormalization scheme uncertainties, PDF uncertainties, parametric uncertainties

Heavy flavor and top quark physics: Contributed Papers

- The ATLAS and CMS collaborations: Physics with the Phase-2 ATLAS and CMS Detectors (Section 4, CERN Yellow report CERN 2019-007)

  New since Yellow report:
  - Projection of top quark spin correlations with CMS at the HL-LHC, CMS-PAS-FTR-18-034
  - Sensitivity to measurements of the SM four top quark cross section with ATLAS at the HL-LHC, ATL-PHYS-PUB-2022-004
- G. Bernardi et al: The Future Circular Collider: a Summary for the US 2021 Snowmass Process (Section 5, arXiv:2203.06520)
- The ILC International Development Team and the ILC Community: The International Linear Collider: Report to Snowmass 2021 (Section 10, arXiv:2203.07622)
- International Muon Collider Collaboration: Muon Collider Physics Summary and The physics case of a 3 TeV muon collider stage, arXiv:2203.07256
- Durieux et al.: HL-LHC and Higgs factory projections for top measurements (arXiv:2205.02140)
- de Blas et al: Global SMEFT fits at future colliders, https://arxiv.org/abs/2206.08326

Heavy flavor and top quark physics: Contributed Papers (cont.)

- S.Aioli et al: Top-quark mass extraction from ttj+X events at the LHC: theory predictions, arXiv:2203.07344
- J.Gombas et al.: Dependence of the top-quark mass measured in top-quark pair production on the PDF at the LHC and future colliders, arXiv:2203.08064
- N.Kidonakis: Higher-order corrections to tt production at high energies, arXiv:2203.03698
- Z.Yu, C-P Yuan: Azimuthal angle correlations as a new boosted top jet substructure, arXiv:2203.02760
- K.Nowak, A.F.Zarnecki: Optimising top-quark threshold scan at CLIC using genetic algorithm, arXiv:2103.00522
- G.Bevilacqua et al: Modeling uncertainties of ttW multilepton signatures, arXiv:2109.15181
- K.Xie et al.: Probing heavy flavor PDFs at hadron colliders, arXiv:2203.06207
- J.Aparisi et al: Prospects for measurements of the bottom quark mass arXiv:2203.16994
- K.Agashe et al: A new method for top quark measurements arXiv:2204.02928

For more highlights see also EF workshop in 2022 and EF workshop in 2021

Heavy flavor and top quark physics: Contributions to the report

- Andre Hoang: top quark mass: theory aspects and challenges
- Tony Liss: Top quark mass measurements from top decays at hadron colliders
- Maria Vittoria Garzelli: Top mass measurements in well-defined schemes from cross sections at hadron colliders
- Frank Simon: Top quark mass measurements at e+e− colliders
- Nikolaos Kidonakis: Top-quark pair and single top-quark production at the LHC: review of theory predictions
- Regina Demina: Experimental aspects of pp→tt and Experimental aspects of 4-top production and EFT contact interaction operators
- Manfred Kraus and Laura Reina: ttX, X = γ, Z, W , H, tt: review of theory predictions for LHC and HL-LHC
- Victor Miralles and Marcel Vos: Top quark coupling measurements
- Aditya Pathak: Precision top quark mass using soft drop jet mass
- Comments: Chip Brock, Marcel Vos, Andre Hoang, others

Top quark mass: theory aspects

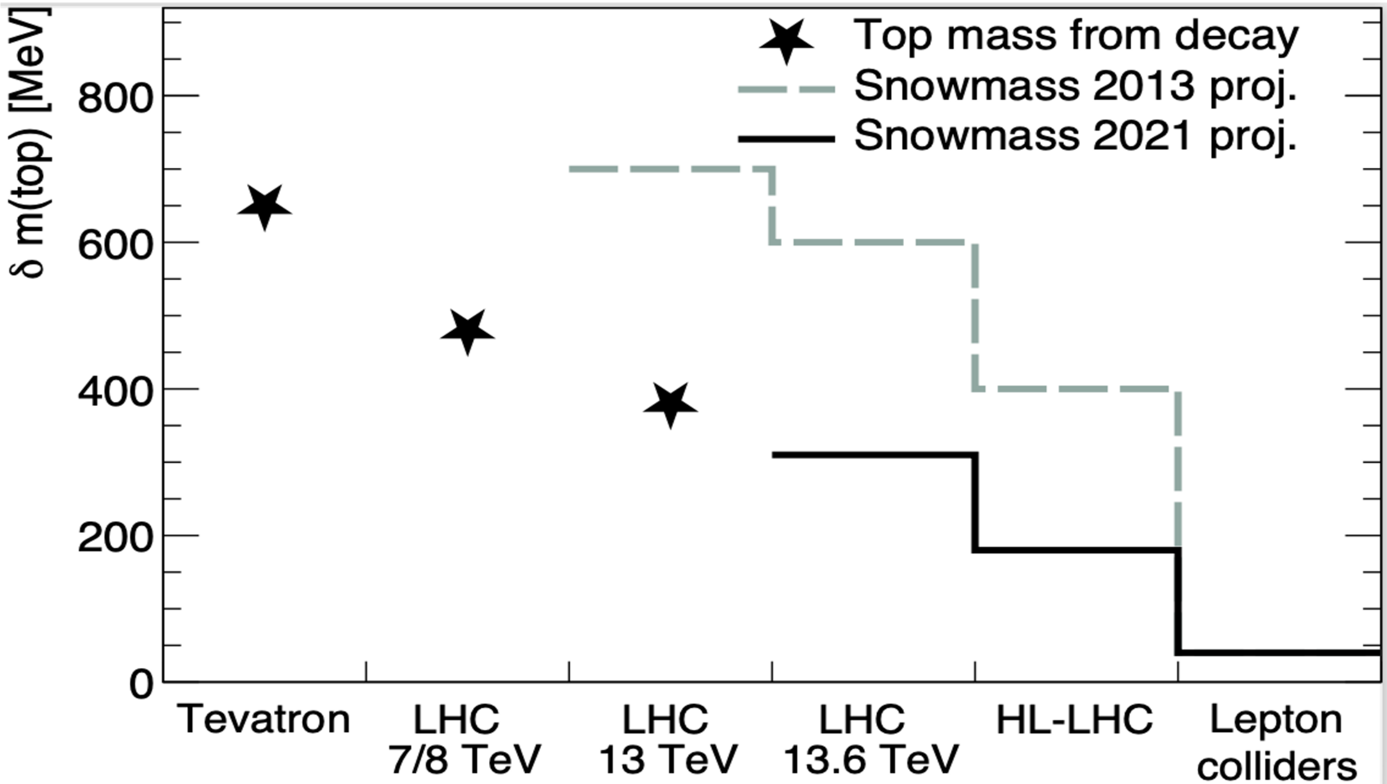
- Top quark mass measurements in a well-defined mass scheme (pole, MSbar, MSR, PS,…) rely on top quark mass sensitive cross sections that can be calculated systematically in perturbation theory.
- Top quark mass from decay sensitive observables at hadron colliders rely on MC event generators.
  - Relation of this MC top mass to a well-defined top quark mass scheme needs to be known at the level that matches the experimental uncertainties (HL-LHC: 170 MeV). Current estimates range from 500 MeV (m_{top} in the pole scheme) to 200 MeV (in the MSR scheme)
- Total inclusive top-pair production cross section based on NNLO QCD calculations using the pole mass as well as the MSbar mass have been determined.
  - Due to a strong sensitivity to the value of α_s and the gluon PDF, the uncertainties of this method are at the level of 2 GeV.
  - A significant improvement of this method relies on a more precise absolute knowledge of the gluon PDF.
  - Reaching uncertainties well below 1 GeV also requires corrections beyond NNLO QCD.

Top quark mass: theory aspects

- The QCD corrections between most top mass schemes are known to $O(\alpha_s^4)$ precision and allow for fixed- order and renormalization group improved conversions with uncertainties at the level of 10-20 MeV (QCD corrections).
  - The exception is the pole mass, which has an intrinsic renormalon ambiguity of 110-250 MeV.
  - Electroweak corrections should also be included.
- Many new ideas are under investigation and it remains to be seen if measurements in well defined mass scheme will be able to compete with direct measurements.
  - Advantage: they do not suffer from the interpretation problem of the MC top mass parameter.
- At $e^+ e^-$ colliders, measurements of the top quark mass in well-defined schemes with low renormalization scales ($R \sim m_t \alpha_s \sim 20$ GeV) with uncertainties at the level of 50 MeV from threshold scans are possible.
  - Precise knowledge on the luminosity spectrum is crucial.
  - Improvements in event generators for full simulation are needed.

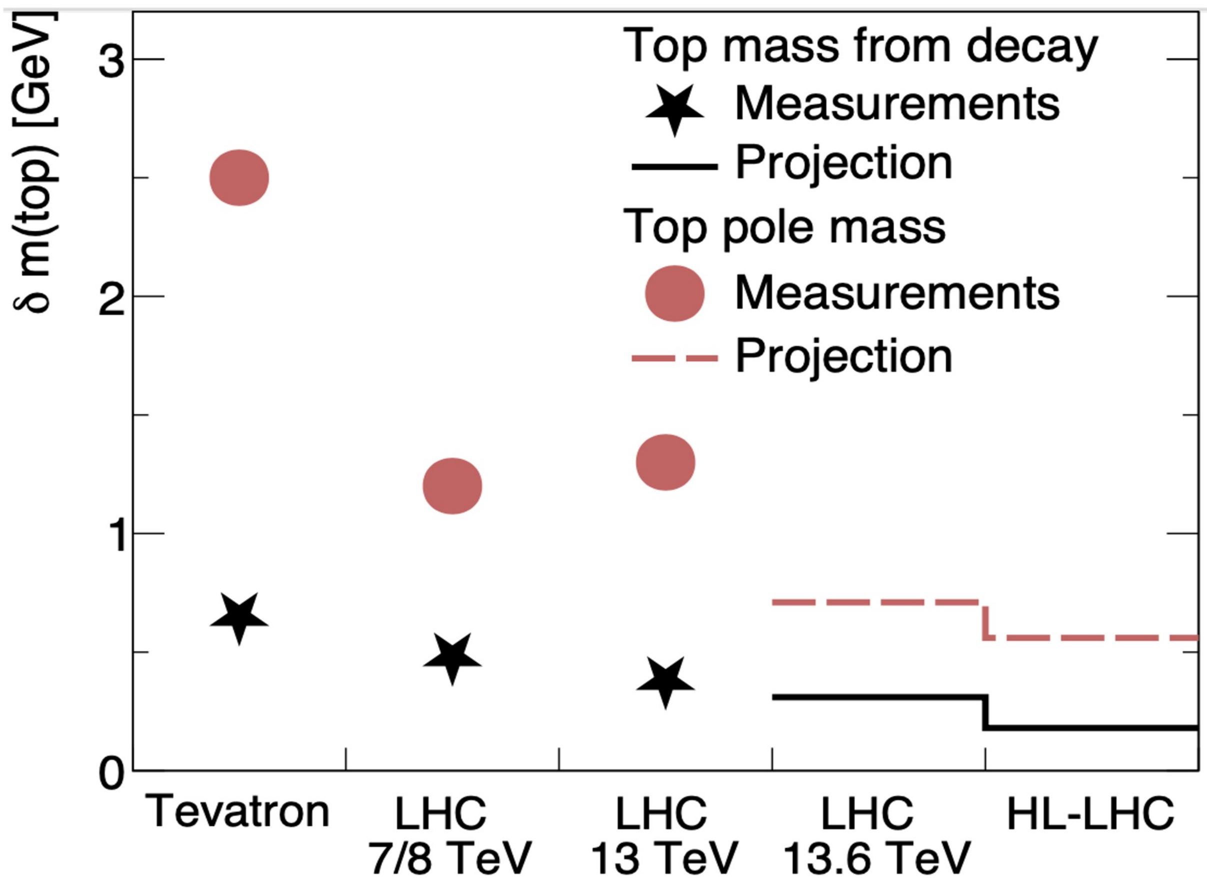
Top quark mass: MC mass measurements and projections

- Comparison to projections from Snowmass 2013



Top quark MC and pole mass at the LHC and HL-LHC

- Direct mass measurements (from decay)
- Top quark pole mass (from production and from ttj)
- Note: Measurements at 13 TeV have not yet been combined between channels

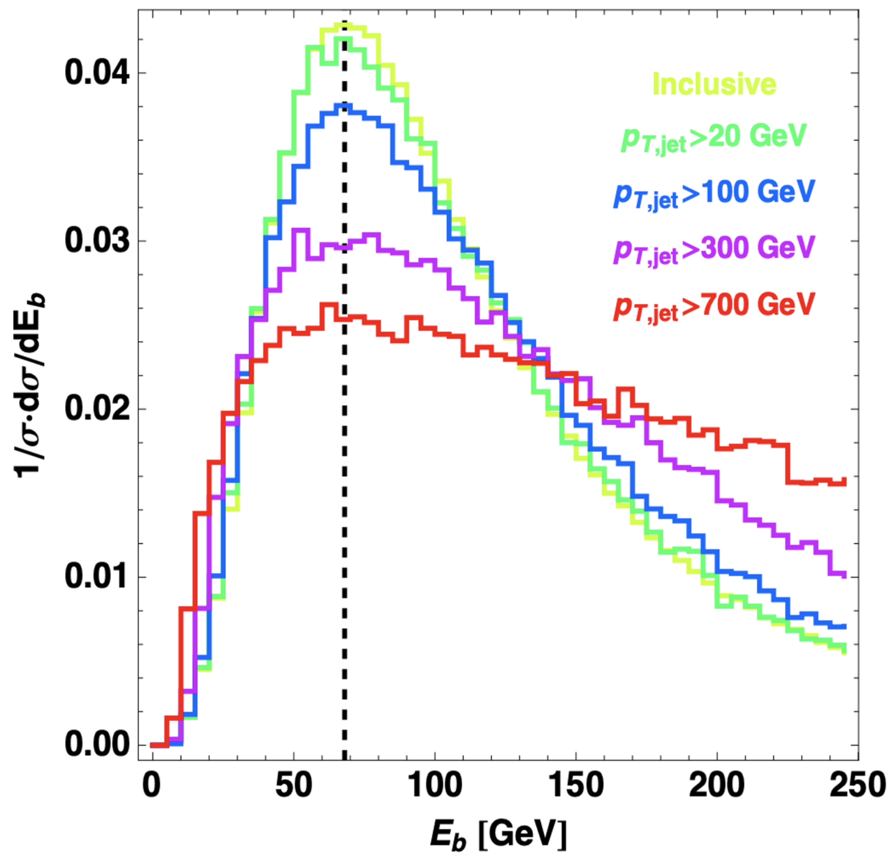


Top-quark MC mass at the LHC and HL-LHC

New idea for MC mass measurements:

- Bottom jet energy, from B meson decay length
- Reduce dependence on top production modeling
- Independent of top p_T
- Reduce dependence on JES
- Residual uncertainties from fragmentation

arXiv:2204.02928



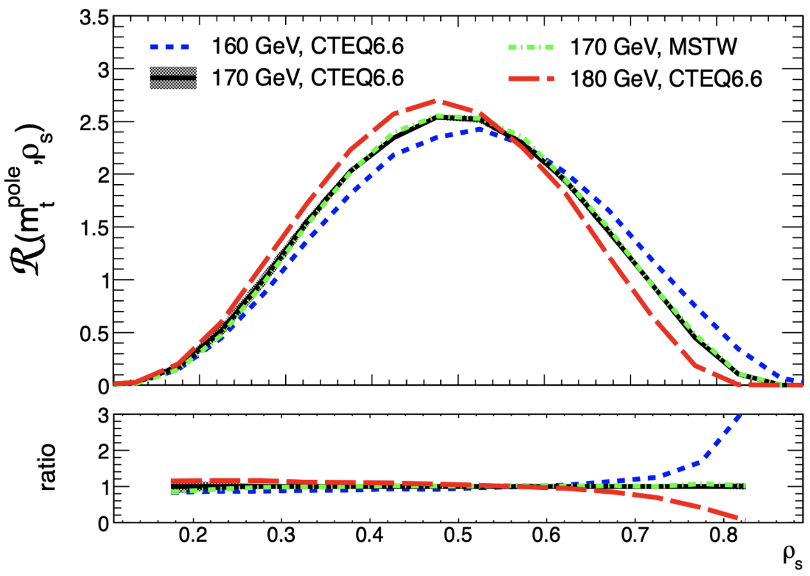
Top-quark mass from ttj at the LHC and HL-LHC

- Top mass in a well-defined renormalization scheme from tt+jet+X
- Sensitive to top mass at turn-on, sensitive variable:

$$\rho_s = 2m_0/m_{t\bar{t}j} \text{ with } m_0 = 170\,\text{GeV}$$

$$\mathcal{R}(m_t^R, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s}(m_t^R, \rho_s)$$

- Unfold to parton level
- Compare to NLO theory predictions
- Study scale, PDF, top mass scheme dependence



arXiv:2203.07344

Top-quark mass from groomed soft drop jet mass

- soft drop jet mass measurement on a sample of inclusive boosted top jets is proposed as a top mass sensitive observable
- concrete comparison of unfolded experimental data and hadron-level theory predictions calculated in a definite top mass scheme becomes foreseeable.

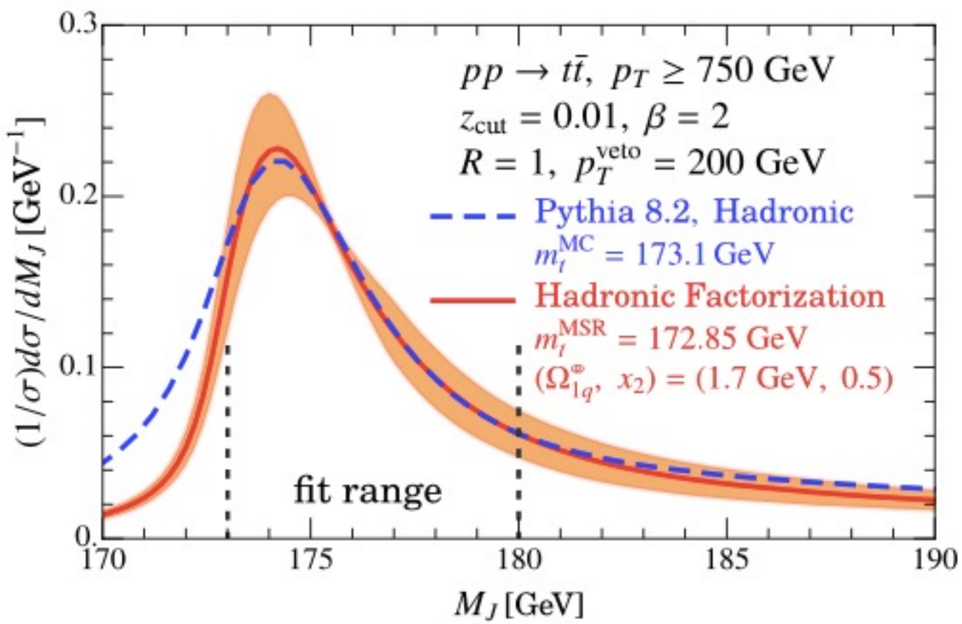


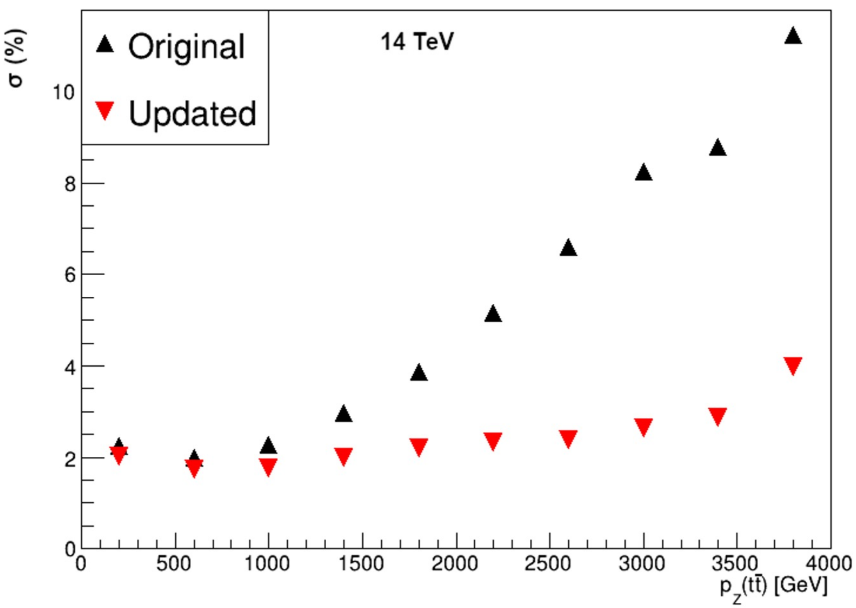
Figure 1-5. *Groomed top quark jet mass spectrum at NLL [55] compared with* PYTHIA8

[arXiv:1708.02586](https://arxiv.org/abs/1708.02586)

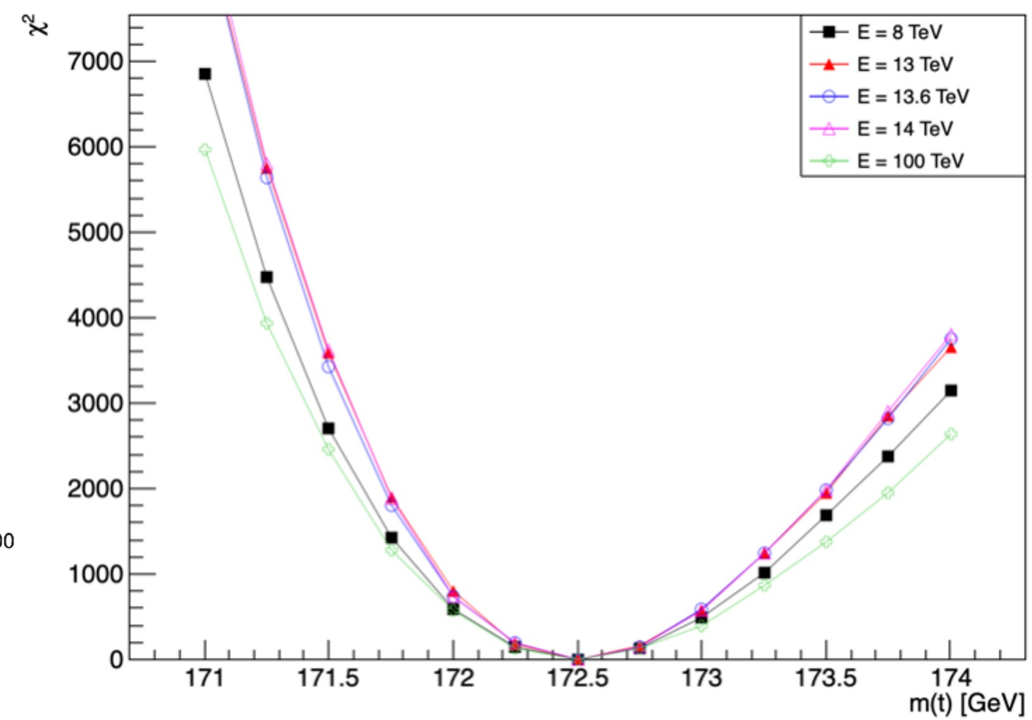
Top quark pole mass and PDFs

- Analysis of differential cross-sections in top-pair production
- Fit top-quark pole mass to m(ttbar), consider uncertainty from PDFs (CT18)
- Constrain PDF uncertainties from p_Z(ttbar), assuming 1% uncertainty
- Top mass PDF uncertainty reduced by ~ factor 2

PDF uncertainty constraint

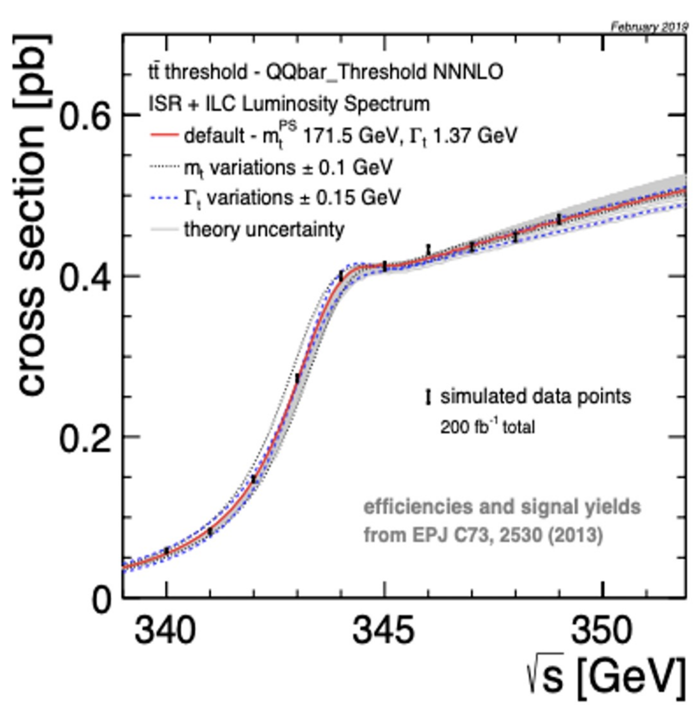


Top quark mass fit

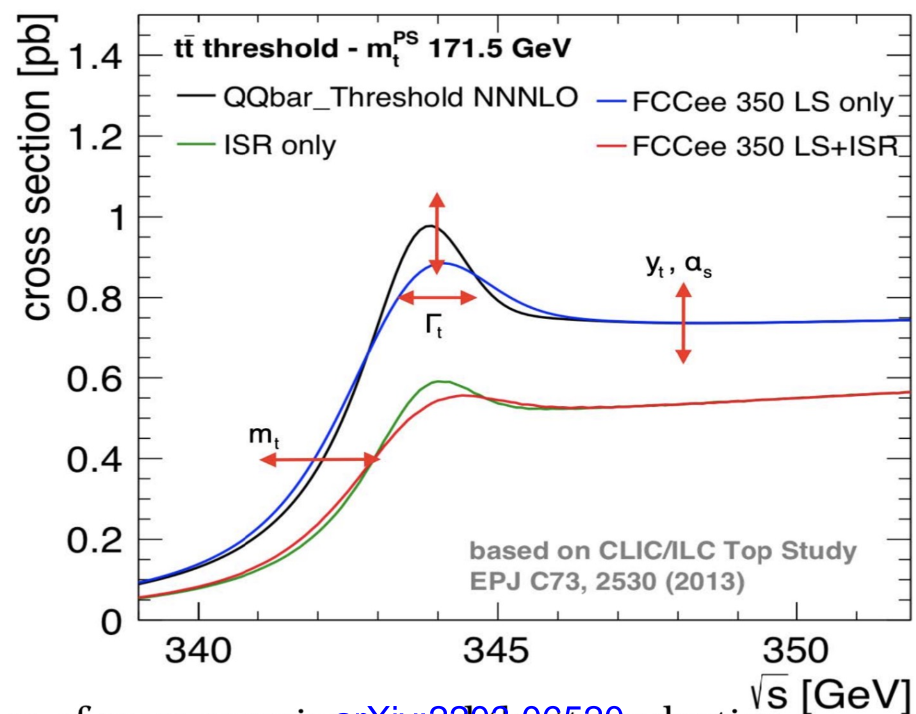


Top-quark mass at linear e^+e^- Colliders (ILC, CLIC, FCC-ee)

- Threshold scan around 350 GeV to determine PS mass
- Can also fit mass, width, Yukawa and α_S simultaneously
- Theo syst include missing higher orders, parametric uncertainty due to α_S
- PS to MSbar mass known at 4-loop, uncertainty: 23 MeV



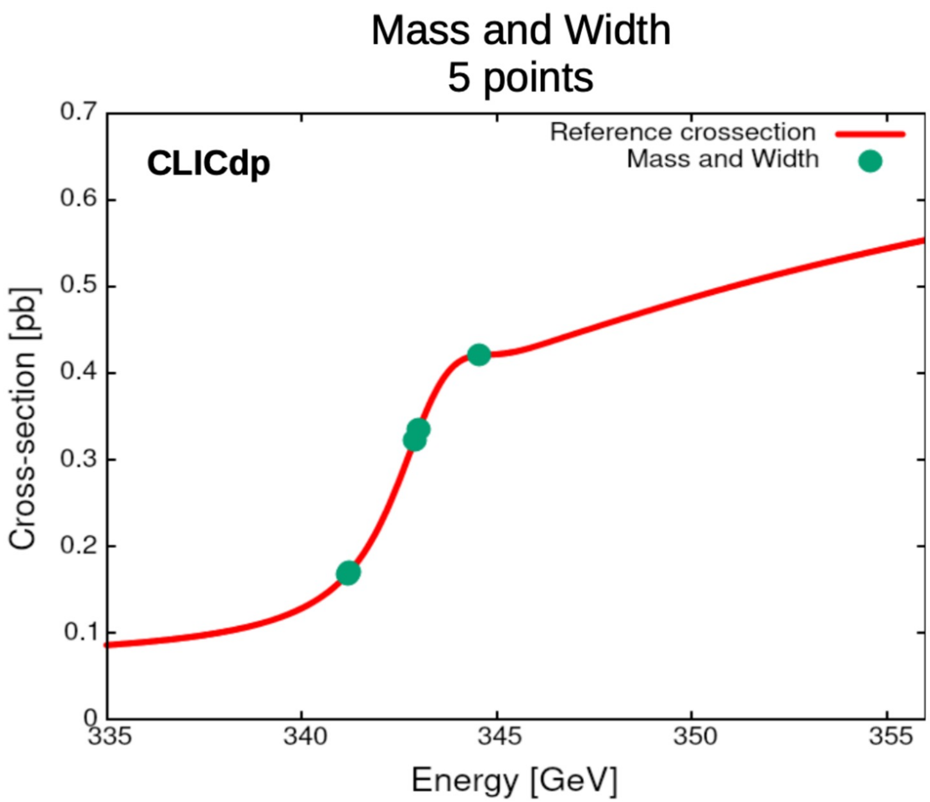
arXiv:2203.07622

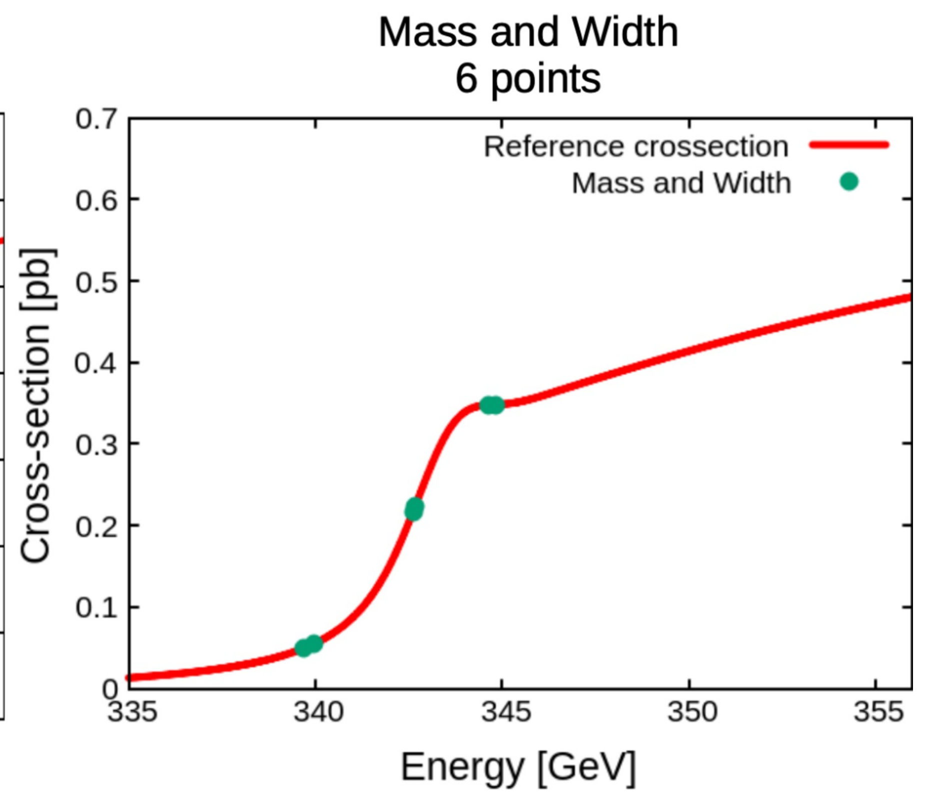


arXiv:2203.06520

Top-quark mass: new idea to improve threshold scan

- Optimize mass scan parameters with genetic algorithm
- Less data to reach same precision (25 MeV)





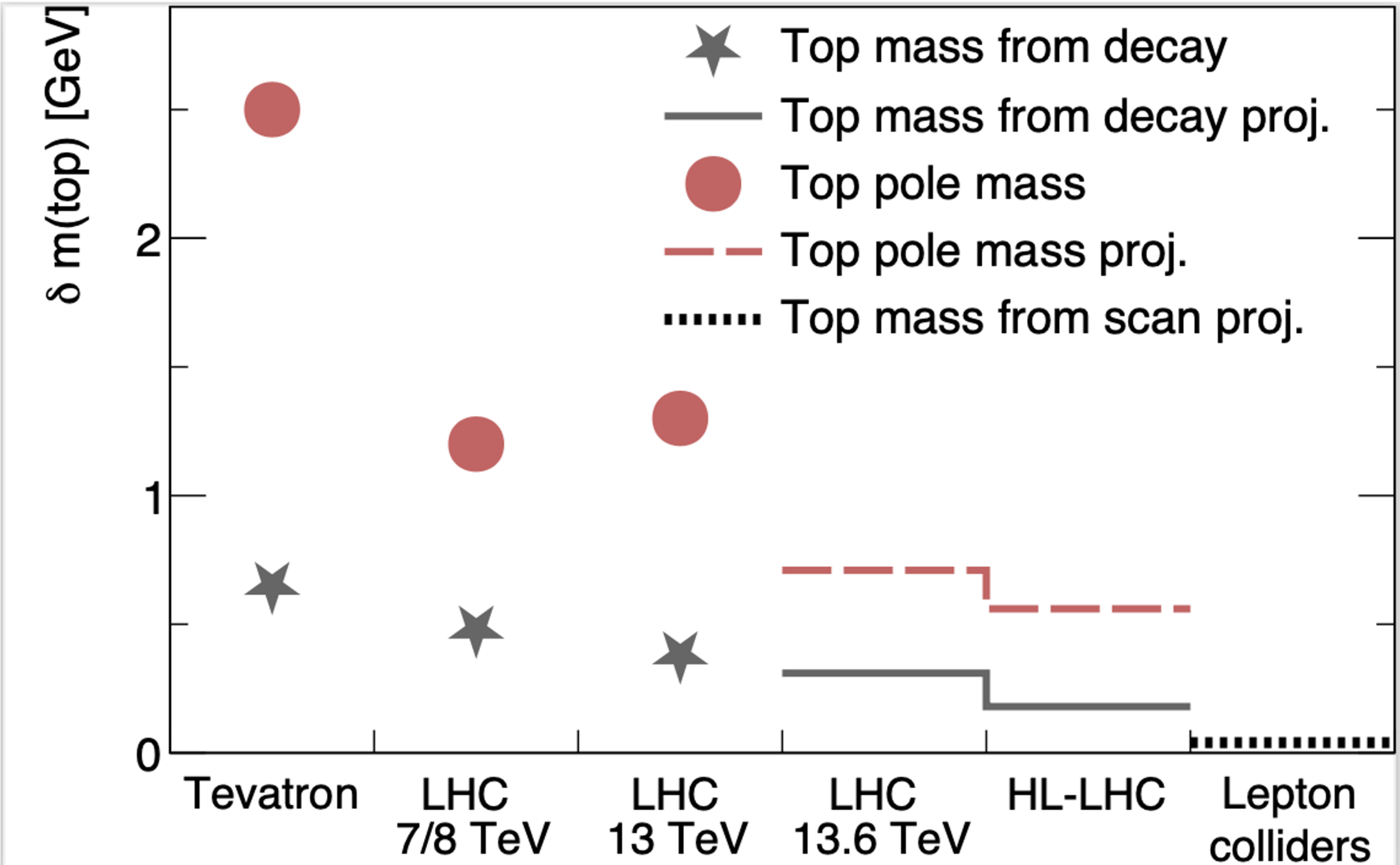
https://arxiv.org/abs/2203.06520

Top quark mass: ILC, CLIC, FCC-ee

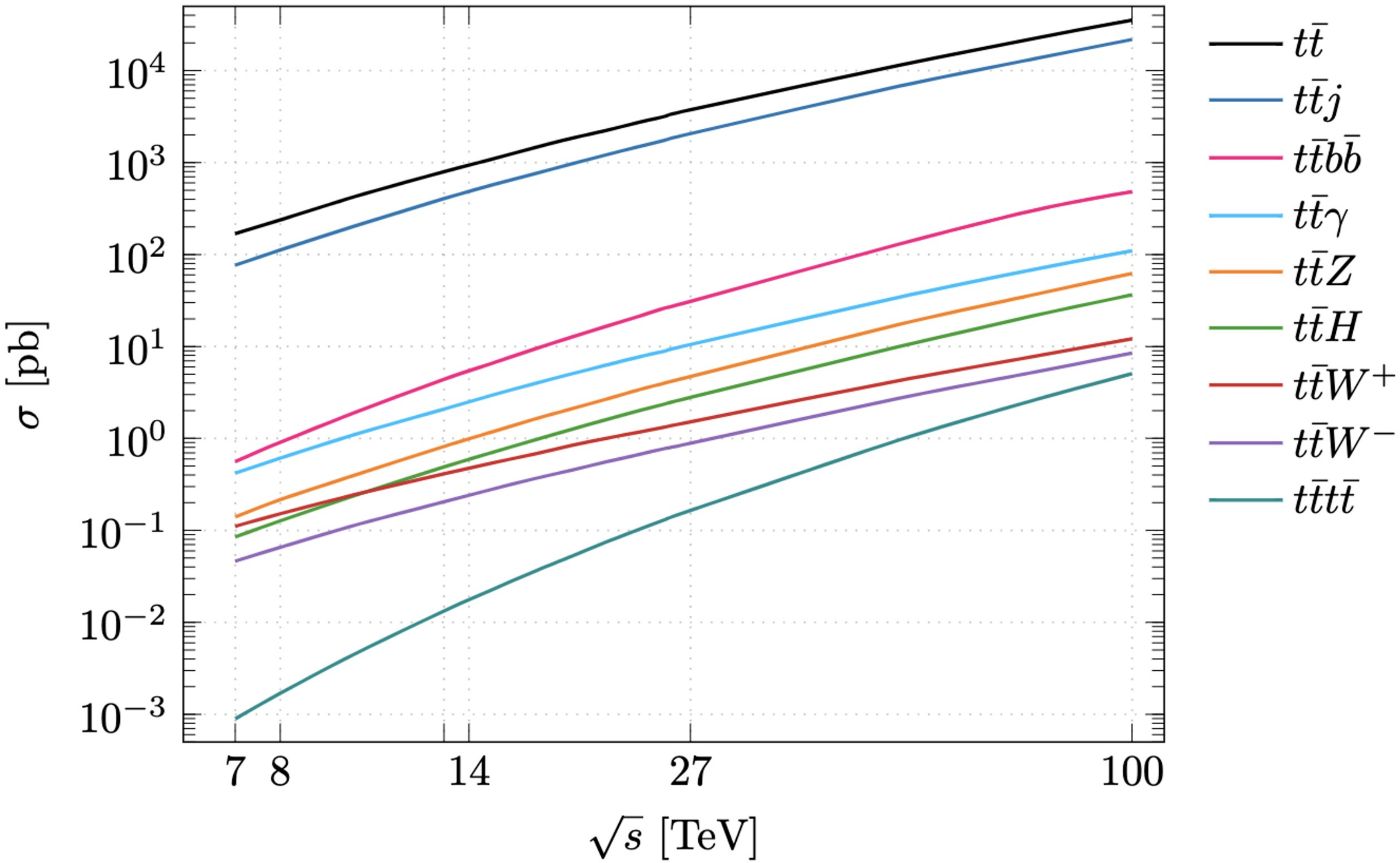
- Top mass from threshold scan at a lepton collider
- Experimental uncertainties should be similar
  - Circular colliders have larger samples, better energy calibration
  - Current uncertainty on $\boldsymbol{\alpha}_s$ leads to 26 MeV top mass uncertainty
  - Terra-Z running at FCC-ee will reduce this significantly

δm_t^{PS} [MeV]	ILC	CLIC	FCC-ee
$\mathcal{L}[\mathrm{fb}^{-1}]$	200	100 [200]	200
Statistical uncertainty	10	20 [13]	9
Theoretical uncertainty (QCD)	40 – 45		
Parametric uncertainty α_s	26	26	3.2
Parametric uncertainty y_t HL-LHC	5		
Non-resonant contributions	< 40		
Experimental systematic uncertainty	20 – 30		11 – 20
Total uncertainty	40 – 75		

Top quark mass projection summary

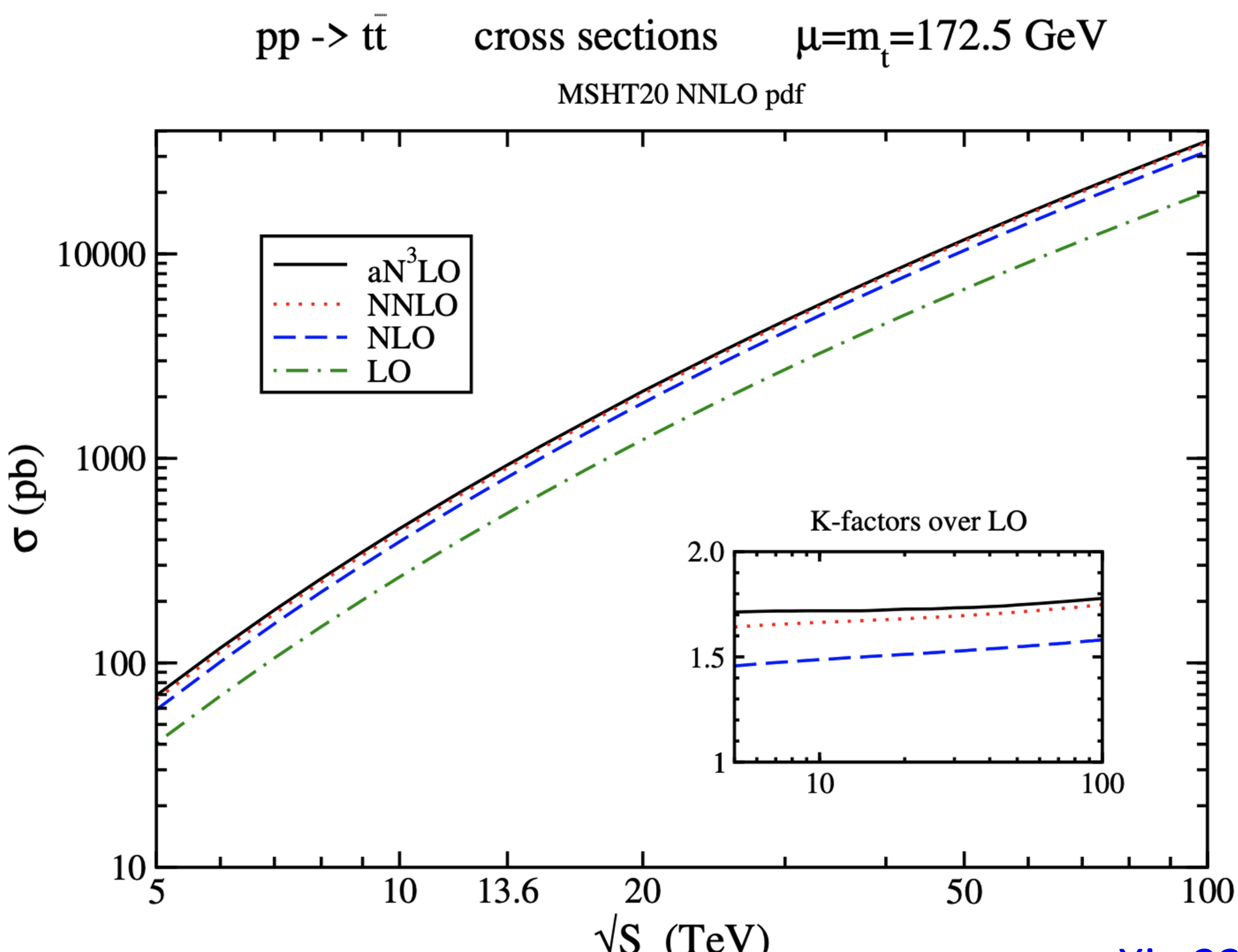


Top quark production processes at hadron colliders



Cross-section at LHC and beyond: top pairs

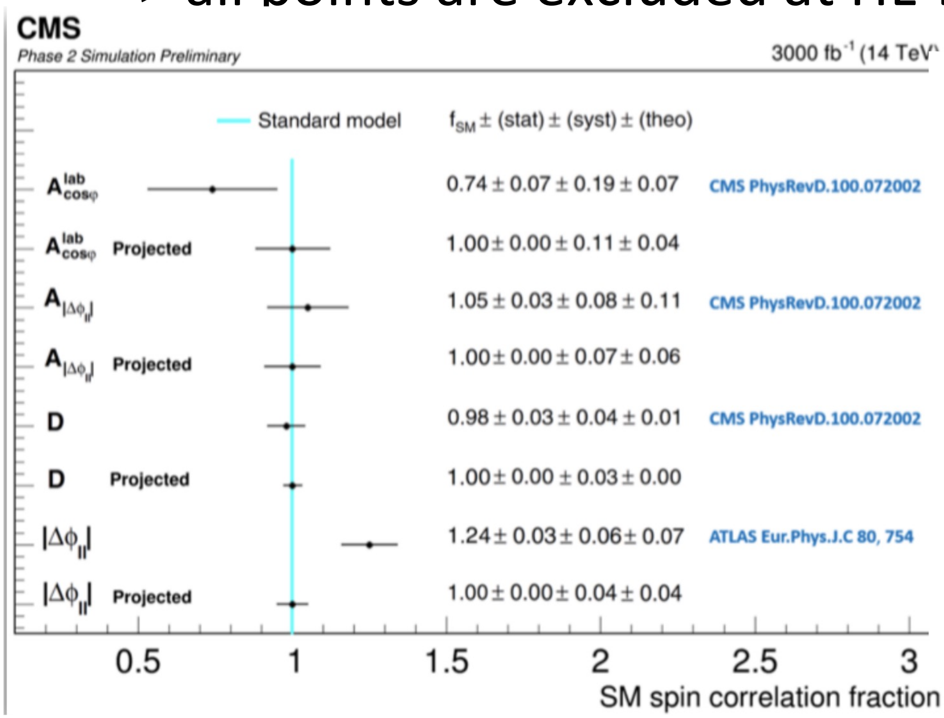
- Resummation of logs, cross section at approx N3LO

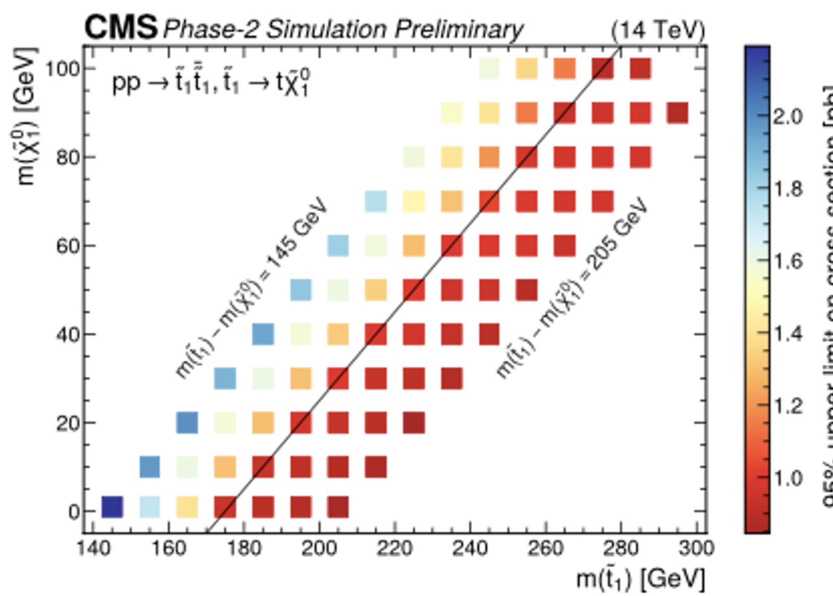


arXiv:2203.03698

HL-LHC top quark spin correlation

- Measure correlation of top-quark spins in tt production
- Project current measurements to HL-LHC
- And set limits on SUSY compressed region: significant increase in the reach of the LHC to discover top squarks
- Stop-pair production cross section is 10-100 pb
  -> all points are excluded at HL-LHC





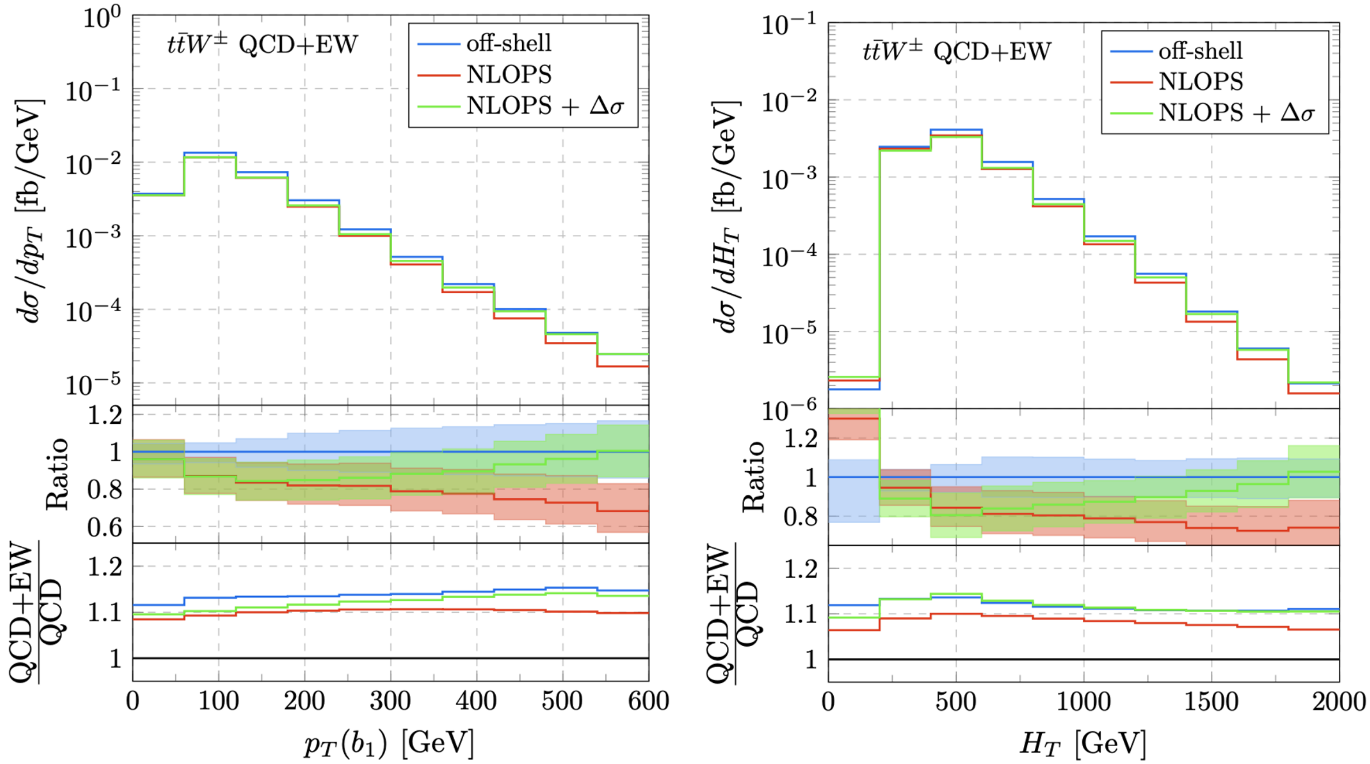
CMS-PAS-FTR-18-034

ttX, X = γ, Z, W , H, tt: theory predictions for LHC and HL-LHC

- ttj: NLO scale uncertainties estimated to be of the order of 10 – 20% at the differential level. First steps have been taken towards NNLO QCD.
- tt γ: NNLO QCD corrections for pp → ttγ become necessary in order to exploit the full potential of future data sets, including in EFT fits
- ttZ: ±8% can be obtained for integrated fiducial cross sections and of the order of ±10% at the differential level (NLO+NNLL), same level as exp. unc: needs further improvements.
- ttW: HL-LHC: factor of 2 improvement needs NNLO.
- ttH: HL-LHC again needs NNLO QCD.
- tttt: Currently, NLO scale uncertainties amount to +- 20% (and 5% PDF unc.), HL-LHC measurement of tttt will be limited by signal modeling. Again further theory improvements are needed (e.g., matching to PS).

Cross sections at LHC: ttW

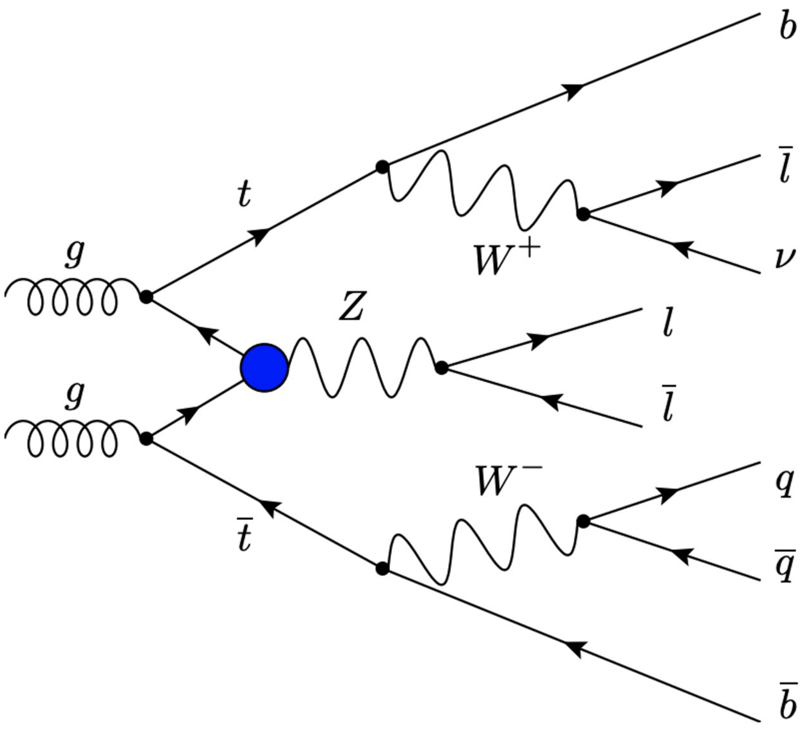
- ttW is background to many measurements and searches (Higgs, SUSY, 4-top, etc.)
- Improved theory calculations, including off-shell tops
- Study of modeling uncertainties: NWA vs full off-shell, generators, parton showers

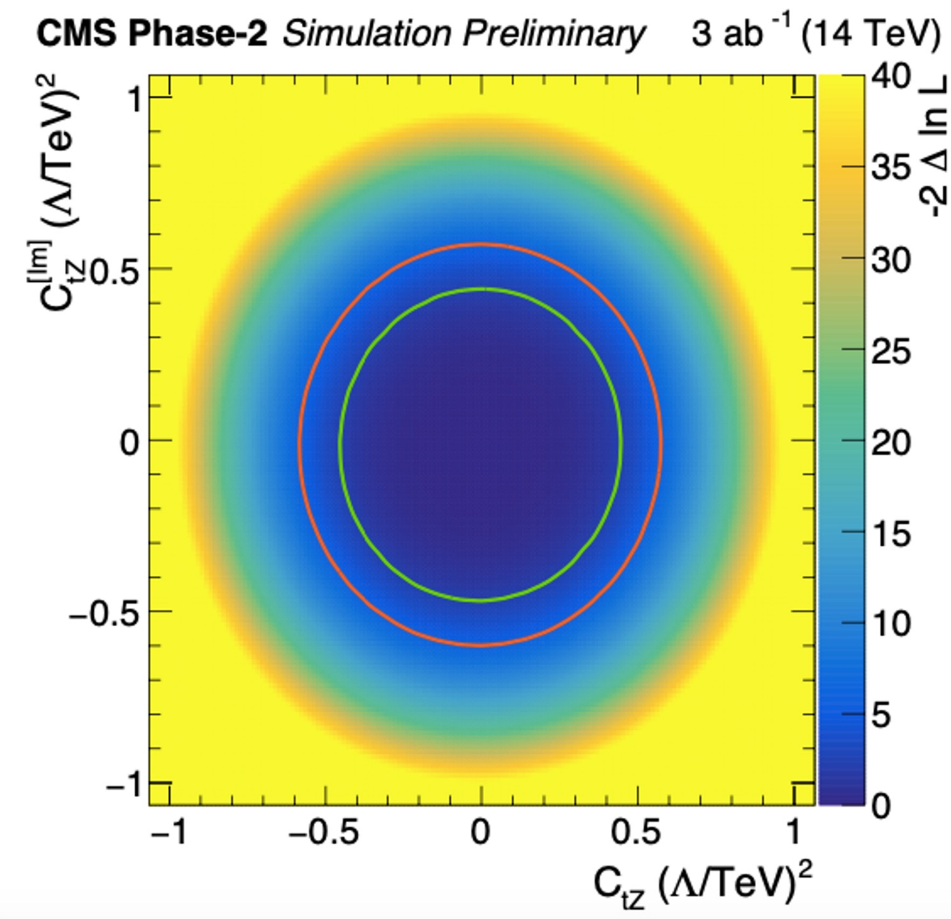


arXiv:2109.15181

Rare processes: ttZ and EW top couplings

- HL-LHC study of ttZ production and EFT operators

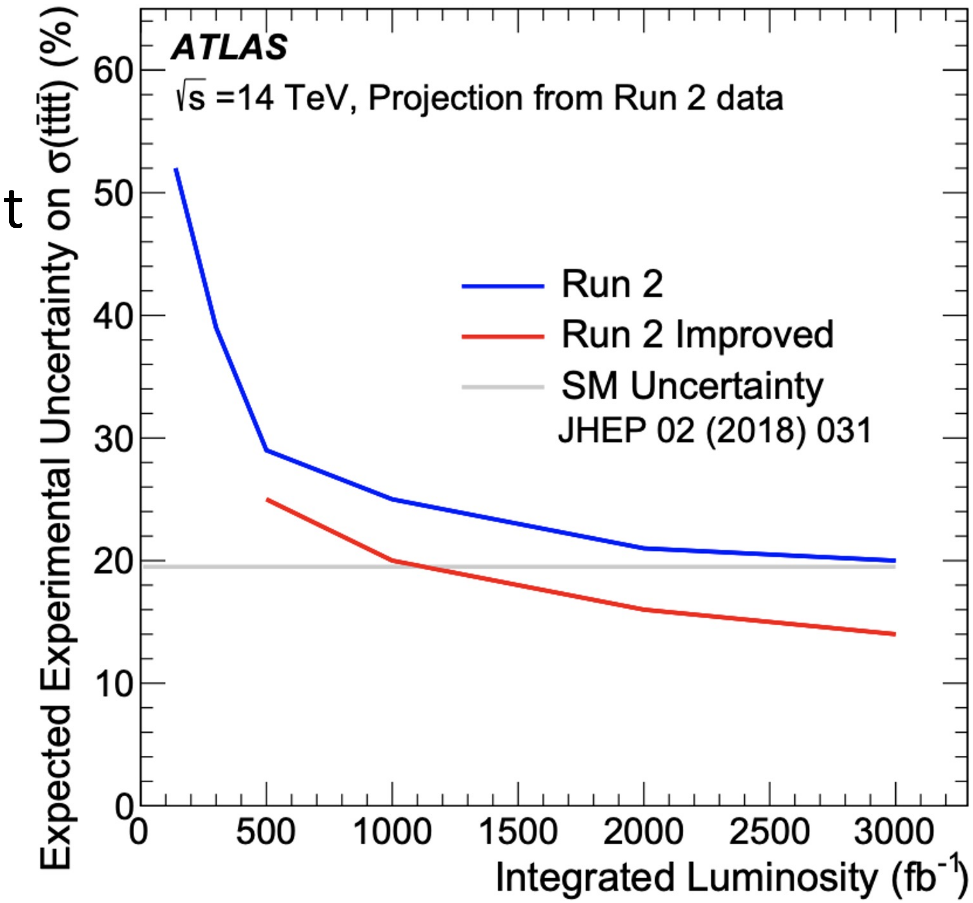




http://cds.cern.ch/record/2652018

Rare processes: Four top production at the HL-LHC

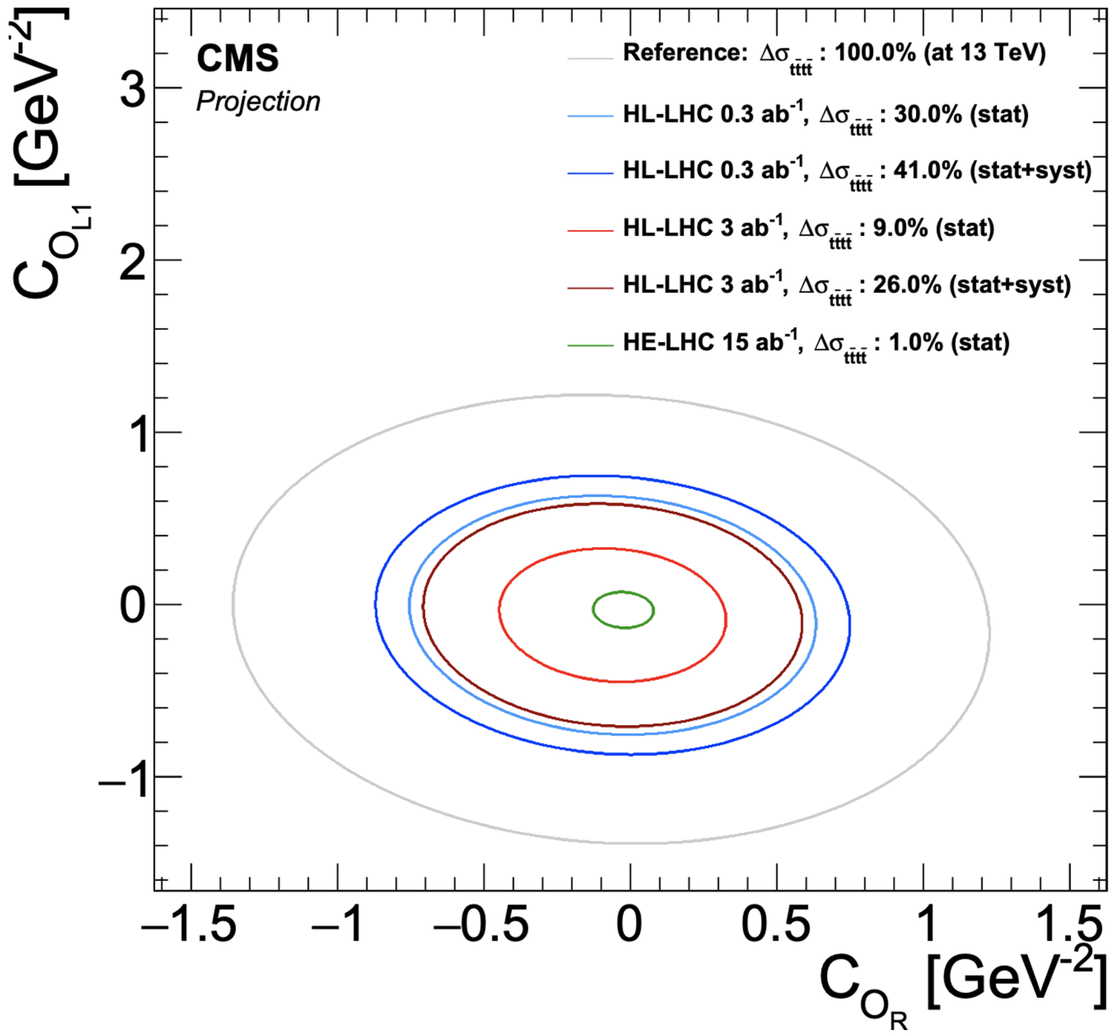
- Extrapolate from existing ATLAS analysis
- Same-sign dilepton, 3-lepton final states
- Measured cross section about 2 sigma above SM
- Extrapolate syst:
  - ½ or scale by lumi



ATL-PHYS-PUB-2022-004

Rare processes: Four top production at the HL-LHC

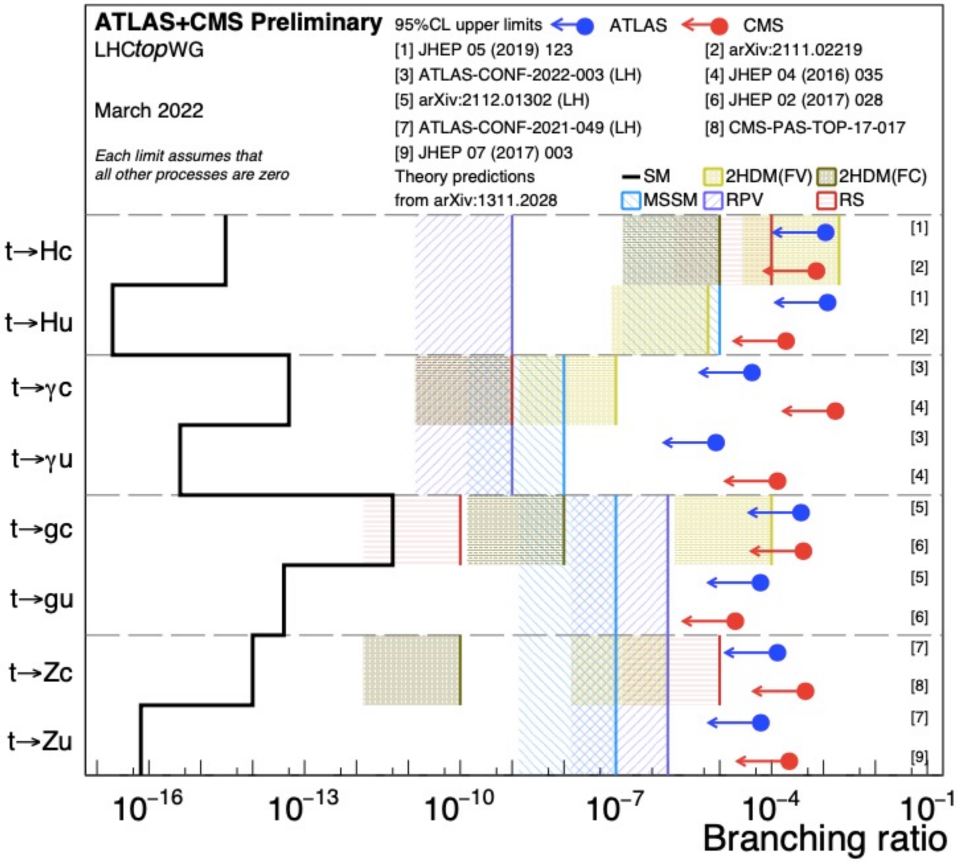
- Extrapolate from existing CMS analysis
- Same-sign dilepton, 3-lepton final states
- EFT operators limits, 4-fermion operators



CMS PAS FTR-22-001

FCNC at the LHC and HL-LHC

- Top quark interactions are an excellent probe of flavor-changing neutral currents (FCNC).



Prospects for the HL-LHC:

B(t->ug)< 3.8 10^{-6}

B(t->cg) < 32 10^{-6}

B(t->Zc,Zu) < 4-5 10^{-5}

B(t->Hc,Hu) < 10^{-4}

EFT fits, top quark measurements

- Top-quark-specific EFT fits
  - Also integrate into global fits
- LEP/SLC, Tevatron, LHC: cross-sections, differential cross-sections, helicities
- FCC, ILC, CLIC: exploit full information in top production and decay

Machine	Polarisation	Energy	Luminosity	Reference
ILC	P(e^+, e^-):($\pm$30%, $\mp$80%)	250 GeV 500 GeV 1 TeV	2 ab^{-1} 4 ab^{-1} 8 ab^{-1}	[451]
CLIC	P(e^+, e^-):(0%, $\pm$80%)	380 GeV 1.4 TeV 3 TeV	1 ab^{-1} 2.5 ab^{-1} 5 ab^{-1}	[452]
FCC-*ee*	Unpolarised	Z-pole 240 GeV 350 GeV 365 GeV	150 ab^{-1} 5 ab^{-1} 0.2 ab^{-1} 1.5 ab^{-1}	[144]
CEPC	Unpolarised	Z-pole 240 GeV 350 GeV 360 GeV	57.5 ab^{-1} 20 ab^{-1} 0.2 ab^{-1} 1 ab^{-1}	[144]

Table 1-9. *Here we show the different working configurations for the future e^+e^- colliders.*

EFT fits, top quark measurements

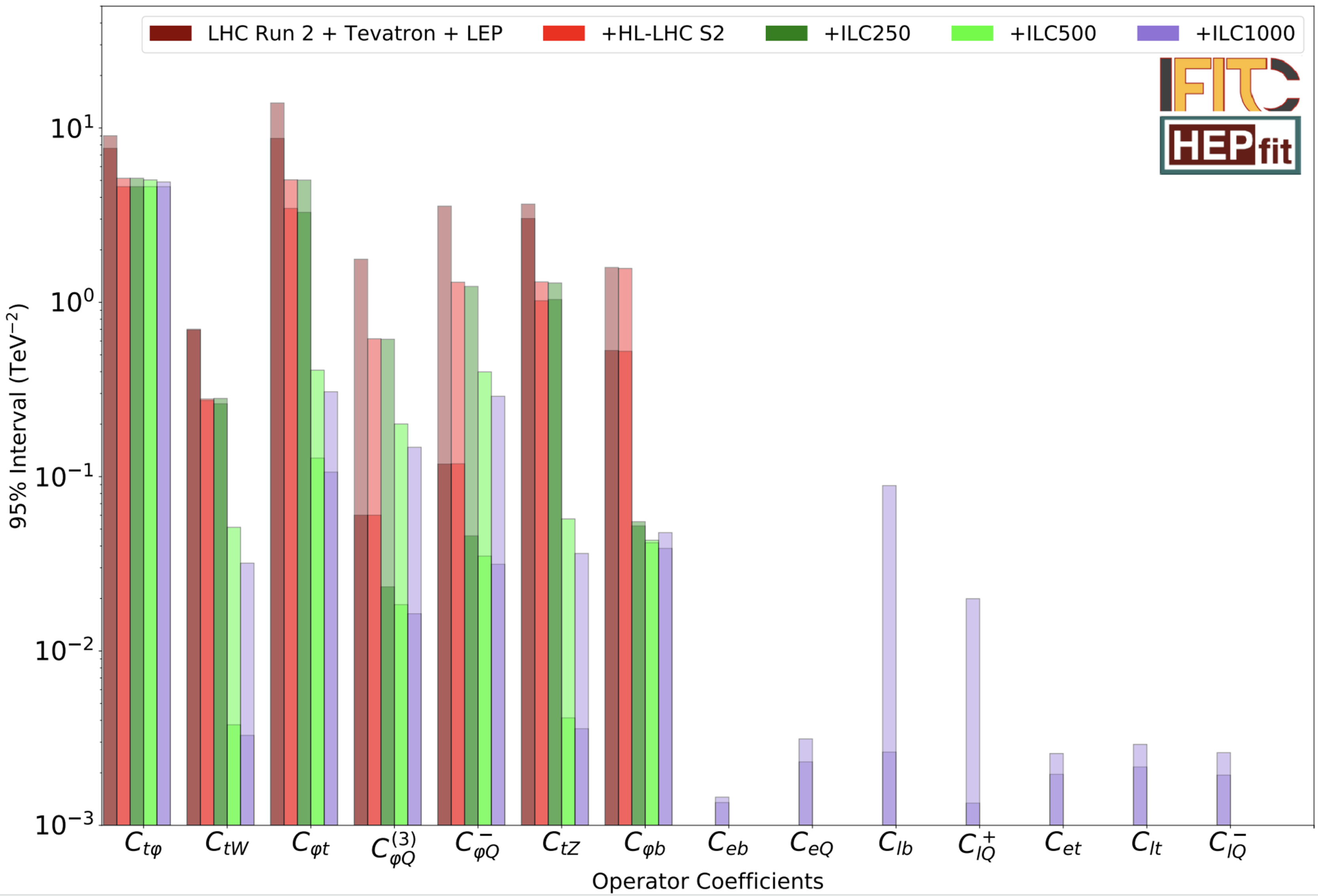
Process	Observable	$\sqrt{s}$	$L_{\rm int}$	Experiment	SM	Ref.
$pp \to t\bar{t}$	$d\sigma/dm_{t\bar{t}}$ (15+3 bins)	13 TeV	140 fb^{-1}	CMS	[34]	[189]
$pp \to t\bar{t}$	$dA_C/dm_{t\bar{t}}$ (4+2 bins)	13 TeV	140 fb^{-1}	ATLAS	[34]	[418]
$pp \to t\bar{t}H + tHq$	σ	13 TeV	140 fb^{-1}	ATLAS	[419]	[420]
$pp \to t\bar{t}Z$	$d\sigma/dp_T^Z$ (7 bins)	13 TeV	140 fb^{-1}	ATLAS	[307]	[421]
$pp \to t\bar{t}\gamma$	$d\sigma/dp_T^\gamma$ (11 bins)	13 TeV	140 fb^{-1}	ATLAS	[250, 251]	[422]
$pp \to tZq$	σ	13 TeV	77.4 fb^{-1}	CMS	[423]	[424]
$pp \to t\gamma q$	σ	13 TeV	36 fb^{-1}	CMS	[425]	[425]
$pp \to t\bar{t}W$	σ	13 TeV	36 fb^{-1}	CMS	[419, 348]	[426]
$pp \to t\bar{b}$ (s-ch)	σ	8 TeV	20 fb^{-1}	LHC	[196, 427]	[428]
$pp \to tW$	σ	8 TeV	20 fb^{-1}	LHC	[168]	[428]
$pp \to tq$ (t-ch)	σ	8 TeV	20 fb^{-1}	LHC	[196, 427]	[428]
$t \to Wb$	F_0, F_L	8 TeV	20 fb^{-1}	LHC	[429]	[430]
$p\bar{p} \to t\bar{b}$ (s-ch)	σ	1.96 TeV	9.7 fb^{-1}	Tevatron	[431]	[432]
$e^-e^+ \to b\bar{b}$	R_b , A_{FBLR}^{bb}	$\sim$ 91 GeV	202.1 pb^{-1}	LEP/SLD	-	[433]

Table 1-8. *Measurements included in the EFT fit of the top-quark electroweak sector. For each measurement, the process, the observable, the centre-of-mass energy, the integrated luminosity and the experiment/collider are given. The last two columns list the references for the predictions and measurements that are included in the fit. LHC refers to the combination of ATLAS and CMS measurements. In a similar way, Tevatron refers to the combination of CDF and D0 results, and LEP/SLD to different experiments from those two accelerators.*

Bottom quark measurements for EFT fit

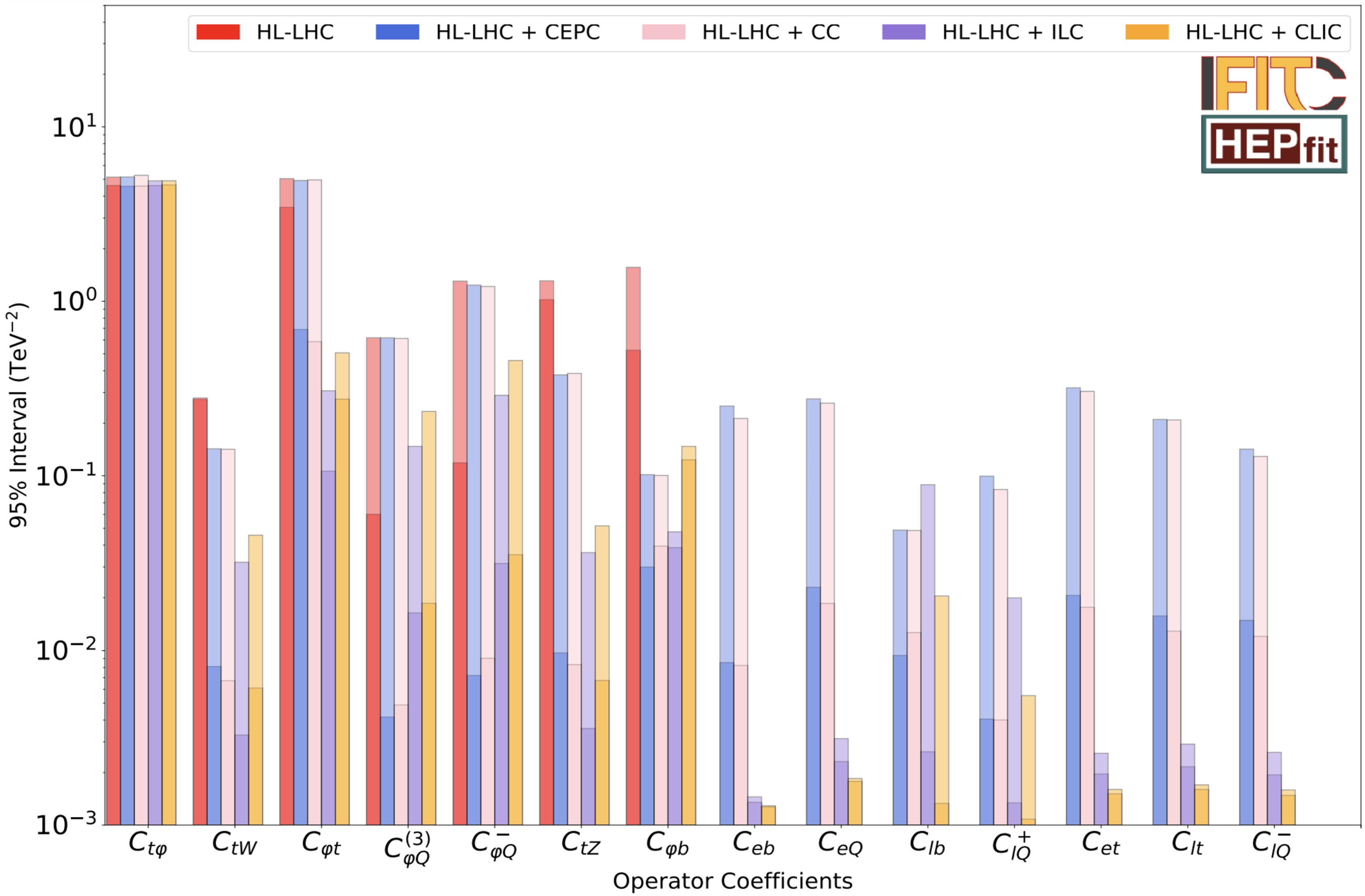
Machine	Polarisation	Energy	Luminosity	Observable
ILC	P(e^+, e^-):(−30%, +80%) P(e^+, e^-):(+30%, −80%)	250 GeV	2 ab^{-1}	$\sigma_{b\bar{b}}$ $A_{\mathrm{FB}}^{b\bar{b}}$
		500 GeV	4 ab^{-1}	
		1 TeV	8 ab^{-1}	
CLIC	P(e^+, e^-):(0%, +80%) P(e^+, e^-):(0%, −80%)	380 GeV	2 ab^{-1}	$\sigma_{b\bar{b}}$ $A_{\mathrm{FB}}^{b\bar{b}}$
		1.5 TeV	2.5 ab^{-1}	
		3 TeV	5 ab^{-1}	
FCC	Unpolarised	Z-pole	150 ab^{-1}	$\sigma_{b\bar{b}}$ $A_{\mathrm{FB}}^{b\bar{b}}$
		240 GeV	5 ab^{-1}	
		365 GeV	1.5 ab^{-1}	

EFT fits HL-LHC and ILC



https://arxiv.org/abs/2205.02140

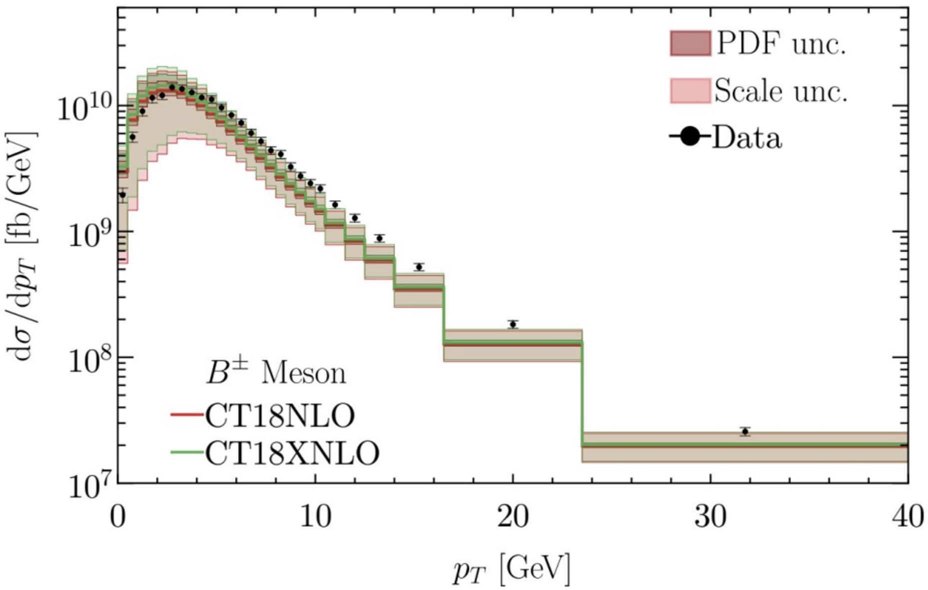
EFT fits HL-LHC and ILC and FCC-ee and CLIC

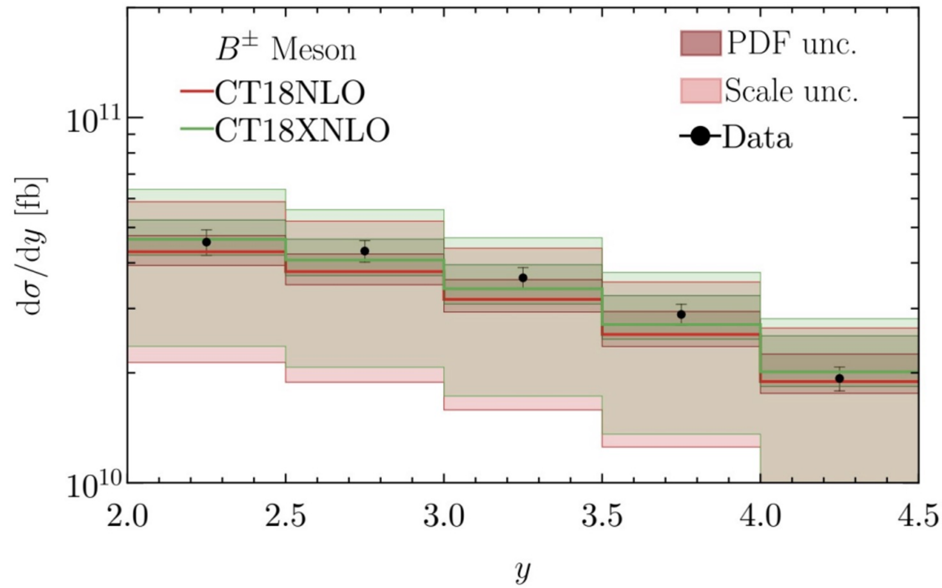


https://arxiv.org/abs/2205.02140

Heavy flavor PDFs

- Study HF PDFs in b-quark hadroproduction in forward region at LHCb
  - probe very small and very large x
- New scheme: S-ACOT-MPS, for charm and bottom
  - Currently at NLO, extend to NNLO to reduce scale uncertainty

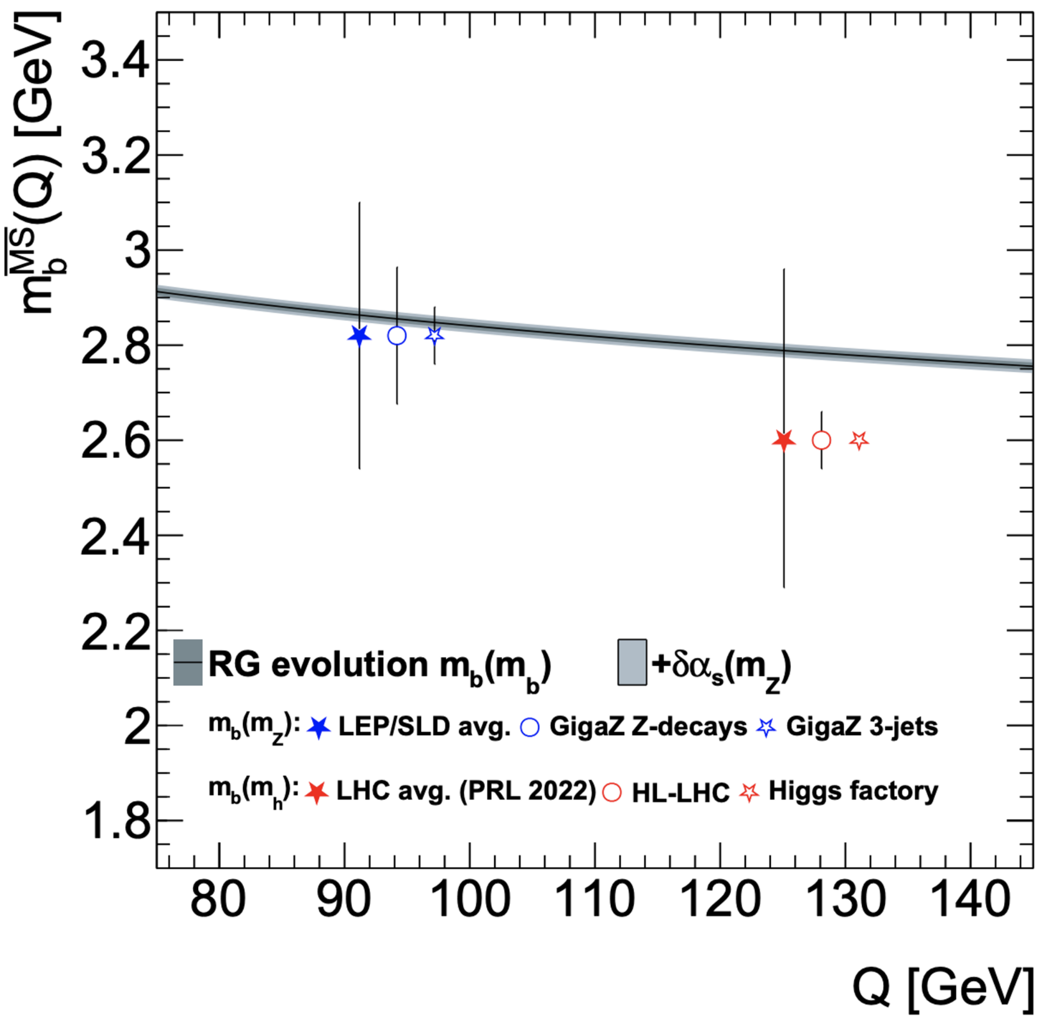




[arXiv:2203.16994](https://arxiv.org/abs/2203.16994)

Running bottom quark mass

- Bottom quark mass measurements from
  Z boson decays,
  Higgs boson decays
- Theory evolution at
  5 loops



arXiv:2203.16994

Summary

- Top quarks play a central role in the exploration of the energy frontier, second only to the Higgs boson.
- The plethora of studies performed for Snowmass 2021 underlines the breadth of topics and the multitude of challenges.
- Of particular importance is the top quark mass, e.g., it is a key ingredient in EW precision fits.
- Rare ttX (X=Z,H,…) processes probe all aspects of the top-quark couplings to the SM bosons.
- Searches for new physics in top-quark final states focus on the third-generation coupling of BSM particles, indirectly through EFT fits or searches for FCNC, and directly through searches for SUSY and other new particles.
- Contact interaction and searches for compositeness are examples of BSM physics that top-quark production is sensitive to at TeV energies and above.

Summary

Comparison of a few top-quark measurements between different future collider options:

Parameter	HL-LHC	ILC 500	FCC-ee	FCC-hh
$\sqrt{s}$ [TeV]	14	0.5	0.36	100
Yukawa coupling y_t (%)	3.4	2.8	3.1	1.0
Top mass m_t (%)	0.10	0.031	0.025	–
Left-handed top-W coupling $C^3_{\phi Q}$ (TeV^{-2})	0.08	0.02	0.006	–
Right-handed top-W coupling C_{tW} (TeV^{-2})	0.3	0.003	0.007	–
Right-handed top-Z coupling C_{tZ} (TeV^{-2})	1	0.004	0.008	–
Top-Higgs coupling $C_{\phi t}$ (TeV^{-2})	3	0.1	0.6	
Four-top coupling c_{tt} (TeV^{-2})	0.6	0.06	–	0.024
FCNC $t\gamma u$, tZu BR	10^{-5}	10^{-6}	10^{-5}	–

Table 1-10. *Anticipated precision of top quark Yukawa coupling and mass measurements, and of example EFT Wilson coefficient for the top quark coupling to W, Z and Higgs bosons, as well as a four-top Wilson coefficient. The expected reach of the CEPC should mirror that of the FCC-ee.*

Summary

Significant theoretical effort is required to exploit the full potential of future colliders.

Examples:

- Calibration of the top quark MC mass to a well-defined scheme with a precision comparable to the experimental uncertainty.
- Computing cross-sections, inclusively and differentially at higher orders in perturbation theory, going to N3LO in QCD for top pair production plus resummation, going to NNLO in QCD for associated production processes, and computing EW higher order corrections.
- Reducing the PDF uncertainties, which are already now the largest theory uncertainties for several processes, most importantly top-pair production.
- Improving the modeling of the full event at hadron and lepton colliders and at hadron colliders reducing parton shower uncertainties.

A sustained and dedicated effort on the theory side is needed already in the LHC/HL-LHC era.

We look forward to your feedback:

Report and Feedback